GasNet^{TM}:

Gas Main Sensor and Communications Network System

Phase I Topical Report

Reporting Period Start Date: March 1st, 2002
Reporting Period End Date: February 28th, 2003

Report compiled by
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and submitted on
February 27th, 2003

as a deliverable under
Contract # DEFC26-02NT41320

for work performed by

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Document Number: REP-GOV-DOE-020303

Notice

This report was prepared with the support of the US Department of Energy, under Award No. DE-FC26-02NT41320. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the Department of Energy.

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ABSTRACT

Automatika, Inc. was contracted by the Department of Energy (DOE) and with co-funding from the New York Gas Group (NYGAS), to develop an in-pipe natural gas prototype measurement and wireless communications system for assessing and monitoring distribution networks. A prototype system was built for low-pressure cast-iron mains and tested in a spider- and serial-network configuration in a live network in Long Island with the support of Keyspan Energy, Inc. The prototype unit combined sensors capable of monitoring pressure, flow, humidity, temperature and vibration, which were sampled and combined in data-packages in an in-pipe master-slave architecture to collect data from a distributed spider-arrangement, and in a master-repeater-slave configuration in serial or ladder-network arrangements. It was found that the system was capable of performing all data-sampling and collection as expected, yielding interesting results as to flow-dynamics and vibration-detection. Wireless in-pipe communications were shown to be feasible and valuable data was collected in order to determine how to improve on range and data-quality in the future.

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I. EXECUTIVE SUMMARY

Gas utilities have little, to no, information about the in situ process variables in their gas distribution networks. This severely hampers gas distribution infrastructure management efforts. Automatika Inc., in partnership with New York Gas (NYGAS[1]) and its associated utilities, under funding from the Department of Energy (DoE) National Energy Technology Laboratory (NETL) Strategic Center for Natural Gas (SCNG), developed the proof-of-feasibility prototype for ***GASNET™***, a stand-alone, distribution pipeline sensor network system for real-time monitoring of live distribution gasmains. The objectives of the ***GASNET™*** program are to provide gas distribution utilities with the information they need to 1) access, maintain, monitor, and repair gas distribution systems, 2) track distribution system related activities - particularly third party activities which may pose safety concerns, and 3) model and design new networks.

GASNET™ is a wireless, self-powered network of keyhole-installed and keyhole-replaceable field-sensors capable of measuring, and communicating wirelessly through the pipe, key process variables such as pressure, flow, vibration, etc. The data is sent in real time to a utility's central-control station. This process information will allow utilities to monitor the delivery process across their entire network from a single computer-console. The ***GASNET™*** system concept addresses 5 key needs of gas distribution network managers. The system can 1) detect certain types of third party damage, 2) enable detection of leaks, 3) result in cost effective monitors and sensors, 4) result in virtual models for gas system analysis, and 5) provide improved and cost effective data acquisition, system monitoring, and control capabilities.

Our Phase I effort for the development and field-trialing of a proof-of-concept ***GasNet™*** system has been very successful overall. The main technologies, ranging from sensing, communications, software and display to in-field installation and safety design were shown to be feasible. The selected sensors and the local microprocessor system were shown in the lab and field to perform as expected. The wireless communications link was also shown to work in a dynamic network setting, with varying operational modes implemented in software (emergency, monitor, etc.). The user interface, even though rudimentary in this phase, was commented upon by utility representatives as being extremely usable and very informative.

Experimental field-testing showed gas flow rates to exhibit highly dynamic and oscillatory behavior varying widely across even a $^1/_2$ mile stretch, in terms of amplitude (flow-rate) and flow-direction as a function of time-of-day. Limited pressure measurements showed that pressures were in the statically-predicted range, however dynamic behavior was not measurable due to premature sensor-failure. Gas temperature and water content were found to be extremely steady, with higher temperatures of the gas flow than ambient (independent of daytime temperature fluctuations). Water content was extremely low and measured at less than 1% by volume. Mechanical pipe-wall vibration measurements proved to only be possible within the vicinity of an instrumented pipe-section due to the segmented and isolating nature of the cast-iron bell-and-spigot design; mea-

1. NYGAS (New York Gas Group) is the association of publicly owned gas utilities in NY State. Through its research and development committee it provides funding and supports a portfolio of innovative R&D projects.

surements did however show that road-traffic could be ignored, while road-surface jack hammering was readily detected, as were impact-loads as small as a pipe-wall hammer-strike.

There were some minor setbacks in the operation of large number of sensors due to the proliferation of drip-rods (which reduced and even eliminated RF-communication links thereby voiding the ability of setting up a pipe-internal wireless network), but overall the concept of live in-situ data gathering, communications and -collection was successfully proven. The decision to test in cast iron mains due to the reduced complexity and cost of field-trials, resulted in a diminished wireless range due to excessive losses in a segmented pipe-network with poorly-conductive bell-and-spigot joints; however we feel this will not be the case at all when welded/bolted medium- to high-pressure distribution mains will be instrumented in succeeding phases.

Utility representatives commented at the conclusion of the field-trials that ***GASNET***^{TM} would have other uses in low-pressure cast-iron mains beyond those of a shorter-range data-gathering and -monitoring system. Proposed uses included (i) the use as a Stoner-model validation tool through measurements over space and time at critical locations, and (ii) use as a capital-project planning tool by serving as a wired/autonomous data-logger to better support engineering decisions.

Based on these results, one can conclude that a ***GASNET***^{TM} system has valid applications in more than one form within the gas main distribution and transmission markets. Sensing and communications options are vast enough to cover any existing utility preference and are upgreadable as technology evolves. The use of the collectable data by the utilities has yet to be explored in depth, in terms of its use as a monitoring, emergency, or even a capital-expenditure planning tool, but we believe this to be only a matter of time before utilities come up with more ways to integrate this data into their daily operations.

AI recommends to NYGAS and DoE a continuation of the ***GASNET***^{TM} program into Phase II. Subject to the feedback from the co-funding NYGAS utility-companies, AI would propose a re-design of the wand to allow for a better separation between the in-side (sensors) and outside (computing, communications, storage, power, etc.) elements for both ease of installation and safety/certification reasons. AI strongly suggest a wireless system expansion to allow for testing in steel mains with user-selectable single-frequency transmitters in various bands and at various power levels to clearly bound the capabilities of a real-time wireless in-pipe system. Furthermore, re-evaluation of the commercial sensor-market, better calibration and sensor-type expansion to suit a larger utility clientele and expansion from distribution to transmission markets will need to be considered. In the end the product being envisioned should allow for a modular installation (CI vs. steel) with a user-selectabeable sensor-suite and an operational mode (data logger, wireless, wired, etc.) to suit the application at hand. We will combine and structure the NYGAS/DoE-agreeable scope into fiscally reasonable and manageable phases with appropriate demonstration milestones and funding decisions.

AI proposes a Phase II in which the effort is focussed on (i) RF steel-communication characterization, (ii) modular wand re-design to allow for no-blow installation, (iii) sensor upgrade/replacement and calibration, and (iv) prototyping the same for a live above ground distribution steel-main medium-pressure ($\leq$ 124 psig; design rated for transmission-pressures though) demonstration at the end of the phase. In addition, design details (i.e. on paper in terms of theoretical analysis and CAD design but <u>not</u> prototyped) should be developed for (a) power-source alternative implementations and associated costs, as well as longer-term below-ground design installations with surface access. A potential Phase III would look at hardening and refining this design and expanding it to a larger-number networked system and its associated demonstration to NYGAS and DoE.

II. TECHNICAL DISCUSSION

1.0 Introduction

Utilities need information about the in-situ process variables in their distributed network with sufficient resolution to enable them to better manage their infrastructure. When a utility lays out a new network, a computer-model of the network is utilized[1] to predict pressures and flows in the system. This allows the utility to size compressors and/or storage facilities, to provide for the necessary flow and pressures. Once installed however, the only real-time monitoring (and control) that occurs in the field is typically at the actual pumping/storage/regulating facilities. This severely hampers gas distribution infrastructure management efforts. Pressure and flow-variables are used to adjust supply and demand from the field - a basic reactive system approach. Additionally, data from every individual gas-meter is collected over time and used for billing in an offline process. Comparison of metered-and-billed volumes and those measured at the supply centers as having been pumped, can give some indication of the state of the network. The power-meter industry has allowed electrical utilities to make a phone-connection with their meter at each dwelling, thereby reading the consumption regularly with minimal manual effort. However, this is not considered a real-time network-wide measure. Gas utilities are beginning to realize the importance of automated pipeline management systems, but they are far from widely applying these technologies.

2.0 Project Overview

Automatika, Inc. (AI) in partnership with New York Gas Group (NYGAS) have teamed and engaged in a Phase I system prototype development and demonstration of ***GasNet™***, a distributed network of multipurpose sensors wirelessly communicating information on the real-time state of the distribution network to utility operators <u>through the pipe-internal void</u>. Through the use of wireless and micro-miniature sensor technologies, ***GasNet™*** is intended to improve the safety and operational capabilities of the distribution network while substantially reducing the cost of operations. ***GasNet™*** is intended to address 5 key issues generic to the gas utility industry, namely **1**) provide improved cost effective data acquisition, system monitoring and control, **2**) result in cost effective monitors and sensors, **3**) detect certain types of third party damage, **4**) result in virtual models for gas system analysis, and **5**) enable detection of leaks in the future. This was intended to be accomplished in a multi-phase program, the first phase of which will be described in this report.

1. so-called ***Stoner*** Model

3.0 Technology Relevance

3.1 Vision and Discussion of Improvement over Existing Technologies

Many technology experts have characterized the upcoming decade as the decade of ***Sensors***. The advent of manufacturing processes developed for the massive and inexpensive production of semiconductors can now be used for the manufacturing of digital and analog sensor devices based on piezo- and micro-machinable and photo-etchable semiconductor materials. In conjunction with the recent advances in micro-machines, Very Large Scale Integration (VLSI) video, and other miniature systems, these manufacturing techniques promise to provide us with sensors capable of measuring various physical parameters and the ability to interact with the physical world; i.e. by actively responding to the information collected via the measurement-devices. In addition, developments in wireless communications allow the distant communication of such sensors/ activators with the user in a real-time fashion. This ongoing development opens up to the utility industry the possibility for a truly interactive, real time communication between utility personnel and their distribution pipeline network system.

Based on this technological transformation of the sensor/communication landscape[1], gas distribution companies have been looking into the potential of using these technologies for applications related to improving the efficiency, management, and safety of the gas distribution infrastructure. NYGAS has concluded, via extensive strategic sessions, that the use of automation technologies by its member companies is the primary source of anticipated operational-leap improvements in safety and efficiency in utility operations. DoE has reached similar conclusions through its own strategic sessions (as evidenced by their publications associated with this and prior BAAs). The DoE and utility industries realize the need to prepare for the next decade of growth, and are looking for innovative solutions to meet their needs (currently 53% of homes in the US use natural gas - by 2020, experts predict a 50% increase in natural gas consumption [DOE/NETL-2000/ 1130]).

GasNet^{TM} represents a technology that promises to offer gas utilities the means to implement such technologies so that they can step up to the new operational level required to meet the demands that customers, contractors, regulatory and local governments will place on them over the next decade. The major advantage of this system is its ability to expand and/or be modified to take advantage of the anticipated emergence of a large variety of sensory devices in the immediate and near future. Such sensory devices could allow us to monitor real-time not only the flow, pressure, and temp/ humidity inside the pipe (which we can accomplish today and will be the focus of this early effort) but also pipe conditioning, gas leakage, third-party interference and pipe movement among others.

In this early development effort proposed here, ***GasNet^{TM}*** will address the immediate need that utilities have for complete, accurate, and real-time data to be provided to the operators at low cost and in real time, describing the state of the delivery network all the way from the pumping/valving station to the point-of-sale (customers' gas-meter). Presently, many procedures for collecting data from critical points of the distribution network (like regulator stations) are through periodic personnel visits to read data-loggers and collect historical operating data, or through off-hour (hence non real-time) wireless individual meter pollings. Centralized gathering, management, and processing of remote and distributed data measurements is the only way to collect real-time on-demand information that will result in substantial improvement is safety and operations. ***GasNet^{TM}*** represents the solution for utilities to accomplish this task.

The proposed ***GasNet^{TM}*** system will provide a new level of operational data type, quality, and granularity previously not available. The technology will impact (i) operations for the utility and

1. With concrete results already present in sensors measuring pressure, temperature, acceleration, etc., primarily in large-volume applications such as the automobile industry.

its contractors; (ii) the use and management of distributed network information; and (iii) real-time and off-line use of information in emergency, monitoring, and design activities for expansion and upgrading the network to safely meet the ever-increasing demand for natural gas. Utilities realize that low-cost, real-time, on-demand, distributed-data access from a network has many uses and is a crucial asset as it will result in large cost savings, safety benefits, reduced customer delivery problems, and more efficient day-to-day management of the distribution network system.

Real-time process-data access from a large network in a central location would help the utility better monitor, control, and supply its network with an on-demand approach. Process-control of the gas-supply through such real-time data-sets would provide information as to size, efficiency, and distribution of supply-nodes to better balance loads, and would allow for better decisions regarding expansion or load-increases in the future. Instantaneous emergency-condition (excess flow/ pressure, out-of-spec acoustic-noise and/or vibrations) detection & reaction would be possible, tightening the safety net and reducing third-party damage potential, especially if combined with third-party access and closeness monitoring capabilities that ***GasNet***^{TM} can provide. If expanded, the ***GasNet***^{TM} sensor network, when teamed with co-located local activation of sophisticated sensing and actuation (valves, stoppers, etc.) devices, would provide for real-time centralized-control interactions for emergency and/or scheduled maintenance activities at a far lower cost than currently required. All of the above points are important if we are to safely, effectively and economically aid the utility-industry in meeting the current and future large increase in natural gas demand projected by the industry and its overseers and regulators in the decade(s) to come.

3.2 Qualitative Benefits

National gas supplies 20% of the world's energy needs. In the US, over 1 million miles of distribution pipelines carry natural gas to almost 60 million homes, representing over 50% of the population. In the Energy Information Administration's Annual Energy Outlook for 1999, forecasted gas consumption by the year 2020 is anticipated to increase by as much as 50%. This increase in demand for natural gas will need to be met by a combination of expanded infrastructure and extended use of existing infrastructure. It is economically infeasible to build enough new pipeline to meet demand. The existing, aging infrastructure needs to be managed so as to extend infrastructure life and throughput without increased safety issues or excessive costs.

In our discussions with gas utilities we have consistently heard that operators and managers feel they have almost no information about their system - they are working blind when diagnosing problems. Utilities generally react to problems that have occurred and rely on delayed data from gas dispatchers and customer calls.   They rarely have information about why a problem occurred and have little operational data that can be used to predict and prevent problems in delivery.

The goals of the ***GasNet***^{TM} program are to provide gas distribution utilities with technical solutions which will provide the information needed to increase infrastructure capacity, infrastructure reliability, and infrastructure safety, and to decrease infrastructure degradation problems. The ***GasNet***^{TM} system will achieve these goals by providing utilities with the information required to 1) inexpensively access, maintain, monitor, and repair gas distribution systems, 2) track distribution system related activities - particularly third party activities which may pose safety risks, and 3) model and design new networks.

3.3 Quantitative Benefits- Rough Estimates

Provision of information to facilitate predictive maintenance and improved pipeline life span.
GasNet^{TM} will provide information on performance and operations which will facilitate proactive maintenance and repair - increasing the useful life of a pipeline. Typically it costs a utility $200 to install a foot of distribution pipeline in an urban setting, and about $50/foot in a rural setting. This is about $1

million/mile and $260,000/mile for urban and rural settings respectively. Assuming that a pipeline lasts 100 years (and the figure is probably less than that), we can arrive at a rough estimate of the cost for a "pipeline year", or the amount it costs to install one year's worth of pipeline for one mile. This cost is an estimate of the costs saved for each additional year added to the life of a mile of pipe. These cost savings amount to $10,000 for a mile of urban pipeline and $2,600 for a mile of rural pipeline. In the case of a small urban utility with about 10,000 miles of pipeline, increasing life span by 1 year could amount to $100 million for their entire network.

Provision of information to facilitate improved capacity for the current system

Expanding the capacity for the existing network removes the amount of additional pipeline that needs to be added to the system to meet increased demand. The information provided by ***GasNet^{TM}*** can be used to determine under-performing areas of pipeline, bottlenecks in the system etc. These can then be improved and optimized. If one conservatively estimates that the detailed operational information from ***GasNet^{TM}*** increases system throughput/capacity by 5%, it would be equivalent to adding 5% more pipeline. For the 10,000 mile utility example, this would be the equivalent of 500 miles. In an urban environment, this 500 miles would cost $500 million to build. In a rural setting, the 500 miles would cost $130 million (using the $1million/mile estimation described earlier). If 5% were added to the capacity of the 1.1 million miles of distribution pipeline in the US, it would save the country the costs of building 55,000 miles of pipeline. This cost varies from $55 billion to $14.3 billion nationwide depending on location. These figures do not consider increased costs associated with pumping/compressing and storing the additional gas-capacity at the source, but they indicate the potential magnitude of the impact.

Detection of safety breaches and third party interference.

Since 1986 there have been 273 fatalities, 1,213 injuries, and a cumulative property damage cost of $235 million associated with gas line operation in the US (Office of Pipeline Safety database - *http://ops.dot.gov/starts/dist_sum.html*). Annual costs associated with safety breaches and third party interference range between $6 and $50 million, with the average being about $15 million. The DOT Office of Pipeline Safety reports that each year between 50% and 80% of these incidents are the result of damage by third parties or outside forces. If one conservatively assumes that 50% of the incidents are the result of third party operators, and the use of ***GasNet^{TM}*** nationwide could avoid 5% of these costs, then annual estimated property cost savings could be: $15 million x 0.5 (accidents resulting from third party) x 0.05 (% accidents avoided) = $375,000. If 20% of the accidents were avoided, this figure would amount to $1.5 million. More importantly, about 20 people die each year, and about 80 people are seriously injured as a result of these accidents. Reducing and avoiding third party accidents would clearly save lives.

Keyhole installation techniques.

Keyhole excavation saves about 65% of the costs associated with accessing pipelines. A typical excavation and repair job costs about $1,000.-, with 800,000 such repairs affected each year in the US alone. For every current excavation that can be achieved with keyhole excavation over $500 could be saved. Developing cost-effective keyhole technologies for this program could save as much as $40,000,000 nationwide, assuming repair systems compatible with keyhole technology are available.

Wireless communication and no-dig pipeline-access capabilities.

GasNet^{TM} would allow for immediate and easy deployment of wireless and untethered inspection and repair systems (autonomous or teleoperated) in the future. Savings could be large, as they compete with costs of manually locating & full-excavation repairing leaks/faults.

3.4 Application Examples and Demonstration of Engineering Breakthroughs

In order to provide a clear image of the potential of ***GasNet^{TM}***, we have listed below just a few of the possible applications of this technology in different operational applications:

- ***Network Data-Relaying/-Collection: Sensor-Data Communication & Transmission***

Utilities currently have a small net of dedicated pressure-sensing stations that they use to collect (typically pressure-) data during the day, and then physically visit these locations to download the data. The more advanced methods, based on retrofitted sensor-stations, allow them to recall said data over a cellular/paging wireless network connection. Since wireless connection costs can be substantial, utilities typically let each station amass data during the day, store it locally, and then recall the data at night/early morning to save call-charges. ***GasNet^{TM}*** would allow all data from all currently-existing sensor-stations to be sent through the pipe to a central data-collection location in **real-time** and **on-demand**. This data-collection location could either be directly at the operations-monitoring offices, or at another remote site, which could uplink the data onto an existing cellular/pager network or an always-on phone line. The benefits here are obviously in the immediate availability of real-time data from the entire network, with drastically reduced data-collection costs (one uplink node irrespective of sensor-nodes, rather than one uplink-node per sensor-node). Hence the ***GasNet^{TM}*** system can serve as a communication-relay system inside of pipes, and add additional pressure/flow/etc. data to the current data-set sought and needed by operators.

- ***Third-Party Access Monitoring: Activity and Closeness Monitoring***

Closeness of third-party activity near gasmains would be possible through the use of integrated vibration- and acoustic (microphone) sensors, which would distinguish excavation and impact-noise and vibration from the background (mostly thermal) signal and report such activity (presence and location) immediately to the control center. In the case of authorized access, 'hooking' into the pipe and imparting an AC EM-field to the conductive pipe, would allow an excavator outfitted with a simple passive coil-sensor to ensure a safe digging distance from the pipe. All in all, ***GasNet^{TM}*** would be capable of providing great safety margin to networks with almost no retrofit to the mains, installation of additional internal or even external sense-wires (such as fiber-optics).

- ***Pumping Station Monitoring: Valve/Manifold Pressure-Drop Monitoring***

Due to the low-cost sensing and computing systems associated with ***GasNet^{TM}***, the system could be used at pumping and regulator stations, to monitor flows and pressures across different 'legs' of a localized valving-, regulator- and distribution-system. The system would collect large amounts of data in a highly distributed fashion, and be capable of up-linking the same over the already in-place wireless connection (cell/pager). Power would be provided locally, and installation of the system would be very straightforward. The data could be used in real time or daily batch-processing modes to monitor and optimize the loads on the network.

- ***Supplier Product Monitoring: Moisture-Content Monitoring***

Urban distribution companies have an interest in monitoring the moisture-content of the natural gas fed to them from the transmission-network company(ies). The ***GasNet^{TM}*** sensors system would be capable of determining in real-time the relative humidity content of the supplied gas at the supply-node, and relay this information to the operations center (again, wirelessly or even over a phone-line). This information is vital to ensuring that the distribution company is receiving product that falls within the specification of what they and their customers are paying for. The only way to monitor this variable cost-effectively is through real-time monitoring and low-cost data-access provided by the ***GasNet^{TM}*** system.

- ***Critical Performance Monitoring: Node-Pipe Junction Monitoring***

Sensor pods could be outfitted with a pressure-, vibration- and acoustic- (microphone) sensor to monitor the state of a pipe-segment close-to or near/in an area subject to high/repetitive third-party damage potential (monitoring for excessive vibration, noise from excavator striking the pipe, sudden pressure-drops, etc.). The pods could be spaced so as to cover a substantial footage of pipe-length and be able to provide measurements over a distributed area. Thresholds set on-board (and changeable though the bi-directional wireless link) would be monitored and warning/alarm messages sent by whichever sensor and transmitted via leap-frog back to an antenna within the pipe and directly to an operator in-situ or via other extension to a computer at a monitoring station.

- ***Problem-Area Monitoring: Transients-Measurement***

The most generic use for the sensor-pod is their use in areas where short- to mid-term monitoring of dynamic conditions over a fairly sizeable area, is to be accomplished at minimal cost and with minimal infrastructure interactions. The application being envisioned, would utilize a few dozen of these sensors placed at key locations of the network over a widely-spaced acreage, monitoring node-points in real time and providing data to a single antenna-port for re-transmission or logging/processing. The notion is to determine through (in)direct sensor measurements what the steady- or dynamic-state of the pipe-network is.

- ***Network-Area Monitoring: Modelling-Data Collection for Verification***

An alternate use of these sensors might also be to provide a low-cost model-verification of the network-design at crucial locations by measuring pressures and flows using the scheme and deployment detailed in the previous bullet, allowing for a computation and verification of design-models in an off-line batch mode.

4.0 Background - Technical State of the Art

In order to better understand the technology subsystem selections for the ***GasNet^{TM}*** system, it is of value to briefly look at the state of technology in the respective subsystem areas that form part of the entire system. This is best accomplished by looking at each major subsystem or area separately, as discussed below; note also that pictorial references are made based on Figure II-2 on page 11.

(i) Sensing - The gas industry has mainly targeted the transmission, processing, and main-node industries and locations/market segments, where accuracy requirements are high, and space and power issues not a major concern (larger pipes, etc.). The industry is only beginning to consider miniaturization of their sensory elements in order to perform measurements on a smaller and more distributed scale. As is obvious, performing such a miniaturization and more compact integration effort is thus a key strategic step for the sensing-industry in this century. There are several main areas that sensors are targeted towards, namely gas-quality and -composition, pressure, and flow. Industry has provided solutions that are primarily targeted at single-point larger-scale production-settings. Miniaturization has had an effect, but has not yet evolved to the point where the industry could make real use of it.

(ii) Integrated Sensor Processing and Computing - Prior-art evidence of computing typically in use with stand-alone sensors or distributed sensors can be found in the industrial automation arena. There, sensors are used to detect events with both binary and analog sensors. Sensor data is typically read directly over a short-run well-shielded cable, or a localized printed circuit board (PCB) molded into the sensor. The PCB takes care of sampling & filtering the signal and packaging it into a certain type of communication stream (serial, parallel, analog, binary, etc.). Hence remote data can be acquired at a central point via direct-sampling or over a distributed communications backbone. Other sensors perform the computation right at the sensor, and pass lower-bandwidth information back to a central decision-making computer over one of several communication backbone types utilizing one of many communication protocols.

(iii) Communications - Communications technology has developed at an accelerated rate, especially at the wireless end of the spectrum. Cell phone technology and wireless networks have driven the technology to a level of miniaturization, cost-effectiveness and bandwidth sufficient for our most immediate needs. This technology is on top of the more established satellite-phone based telephone and the paging network systems already in use since the 1970s and 1980s. Since then, wireless LAN technology for ethernet and BlueTooth personal communications standards and hardware have begun dominating the market in customer and light industrial applications. Other solutions range from PC-Card products, to integrated, to embedded solutions for wireless communications, whether serial- or ethernet. Software protocols and easy connectivity have played a large role in making wireless communications more widely usable and maintainable. The notion of using data-over-wire/-air to allow gas companies to collect field-data has been an important factor in reducing companies operating costs, whether this be for meter-reading or other more process-related variables. Within the processing/valving/pumping/compressor station of a gas utility, process variables are typically conveyed over a wire-carrier using either current, serial or other protocol streams. Exchange of data with other location can then occur over an intranet and/or the internet, or even over a telephone line. Field-data, such as meter-readings, can be conveyed either over a phone-line (akin to those used by power companies to read customer meters), a paging network, or even a radio-frequency based communications network. Such systems are known as AMRs (Automated Meter Readers), with a wide selection available.

To counter the commonly misheld opinion that wireless RF-communications inside pipes is not feasible, we offer the experimental results developed by CMU as part of another DoE-funded project with NYGAS under the Gas Infrastructure Reliability Program. Said program has positively proven that wireless communications inside of 6-inch diameter steel pipes via wireless 2.4 GHz ethernet OEM LAN hardware utilizing the DSS-protocol, even at low power-levels (6mW), is feasible to ranges of 2,000+ feet at data-rates of 11 to 1 Megabit/second. Smaller pipe-diameters will have larger ranges, while larger pipes will have shorter ranges. These pipes need not all be straight, and the experimental data accounted for bends, Ts, Ys, etc. A figure of the attainable coverage over a 1,000 ft. x 1,400 ft. plate-area of gasmains in an urban neighborhood (original utility Plate with blocked out details for data-security reasons) utilizing an OEM *Orinoco* laptop LAN-card with a remote patch-antenna, is shown in Figure II-1 below:

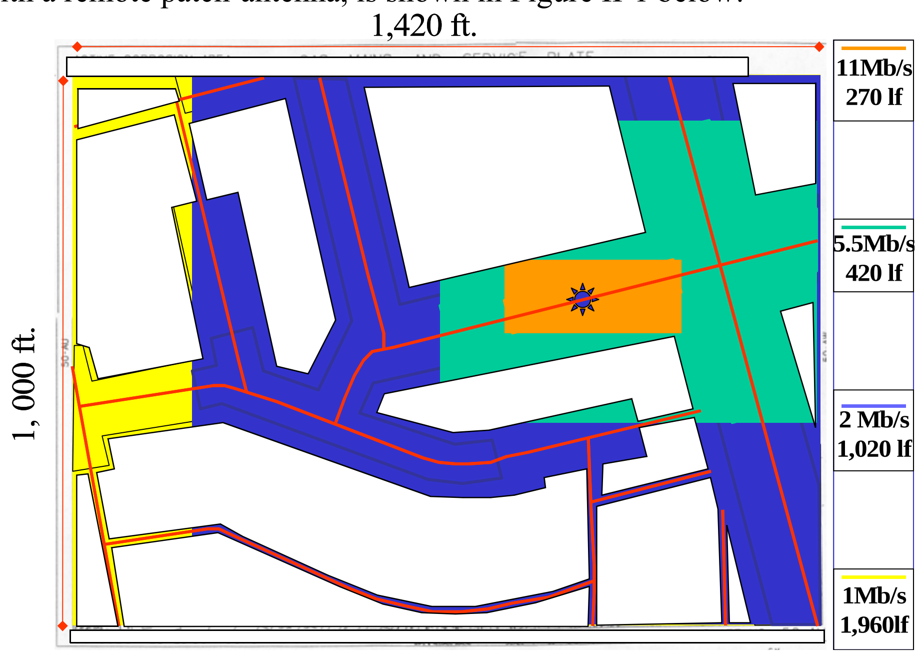

Figure II-1 : Wireless 2.4 GHz RF coverage for OEM LAN-card with a patch-antenna at variable data-rate over 1.4 Msq.ft. area (2,200 lf of mains) covered by 2,200 linear feet of high-pressure distribution mains.

(iv) Power - The use of stand-alone field-equipment is well-practiced. Meteorological stations and other remote- or long-duration systems work in environments with little human supervision or interference/support. Power, and its availability, is one of their main considerations when it comes to developing such units. This criteria is no different for any process- or field-equipment in use by gas utilities. The need to power sensors and computing is typically solved through hardwiring (if accessible) to the local power-grid (long-term solution), solar-powered battery-bank (low-power long-term solution), generators (short-term use), to power-cells/batteries (shorter-term use unless rechargeable). Gas- and power meters that are remotely interrogated are typically powered by the residence power-net. Sensors that operate on very low power and need not be accessed often can get away with primary (non-rechargeable) cells, while others where access is possible, will use rechargeable cells.

(v) Live Gasmain Access - The newer methods of accessing live gasmains have revolved to this date around the deployment of both camera-internal inspection and repair systems. ARIES (Niagara-Mohawk-funded), MEI (GRI-funded), Consumers Gas (ConEdison co-funded), and NICOR (Gaz de France funded) have all developed access-systems for different specific equipment. Such access-systems require the use of a backhoe for mechanical excavation of a complete (typically) 6-foot by 4-foot hole, which on average can take up to an hour and cost $750.- (incl. restoration). Keyholes, typically no more than 2-foot by 2-foot by up to 6-feet deep or more, can be excavated pneumatically using a poker-bar and a suction-hose from a vacuum-truck. Keyhole excavation is fairly common if topside pipe-access only is required and the location of the pipe is accurately known. Some keyhole excavations utilizing vacuum extraction have been successful in emplacing a circular screw-on clamp onto low-pressure mains - higher-pressure mains have so far been unfeasible. British Gas has supposedly developed a new fully-functional keyhole excavation system, but data is not yet publicly available.

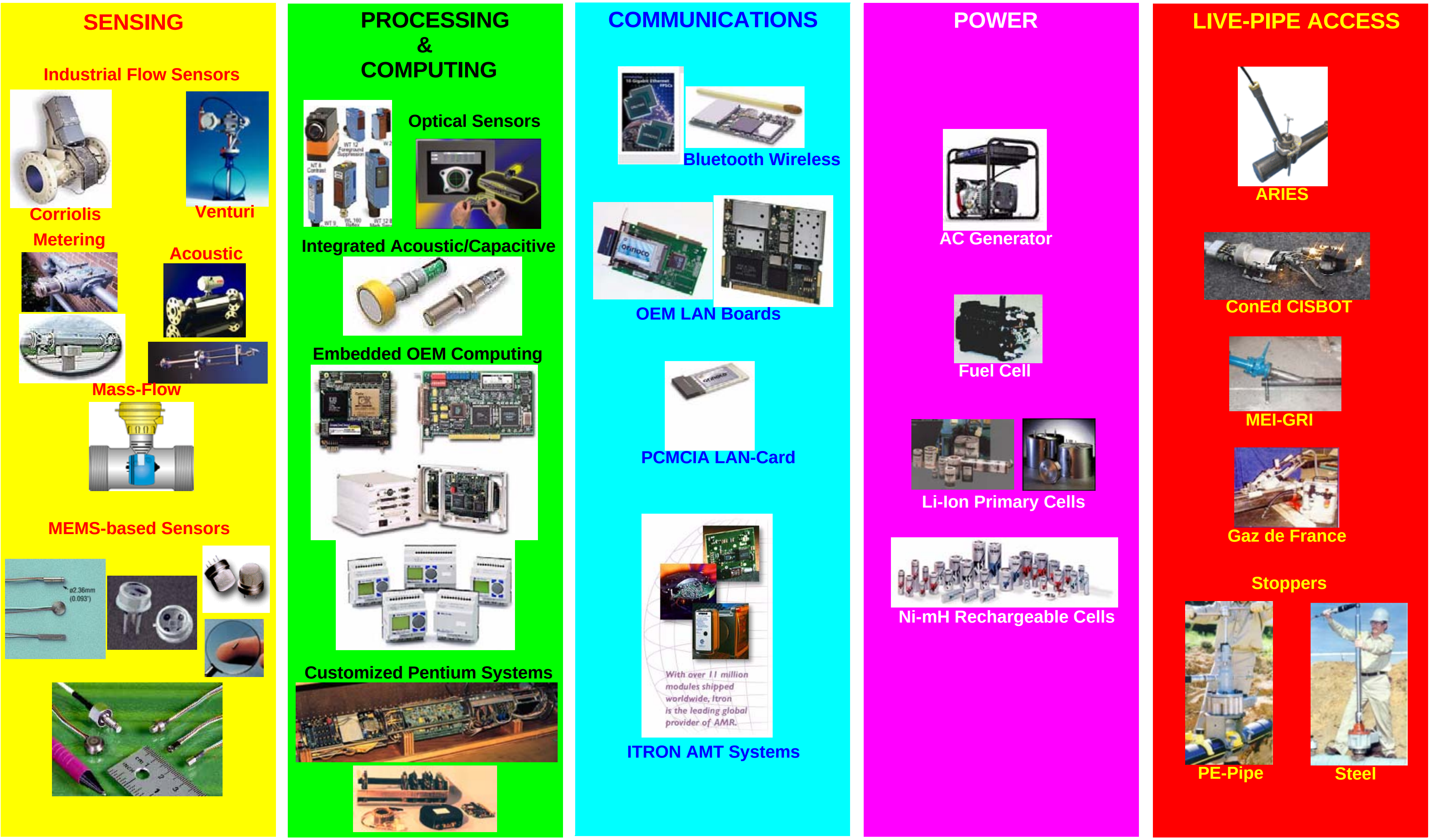

Figure II-2 : State-of-the-Art picture gallery covering sensing, sensor-processing and computing, communications, power and live-pipe access

5.0 System Design Concept

5.1 Overview

GasNetTM is a wireless, self-powered network of keyhole-installed and keyhole-replaceable field-sensors capable of measuring, and communicating key process variables wirelessly through the pipes. These variables can cover a wide range of operating parameters, depending on the availability of appropriately sized and accurate sensory devices. For our engineering and initial Phase I effort, the system was designed around measuring variables for which appropriate off-the-shelf sensor technologies was available (such as pressure, flow, vibration and moisture-content). The data in our preliminary field-trial set up was simply sent between sensor-wands in real time. This process information then allowed utilities to monitor the state of the delivery process across the monitored network section from a single computer-console. The Phase I ***GasNet***TM sensor-wands were developed for natural gas distribution infrastructure (namely low-pressure cast-iron networks), however, the envisioned system is also intended to be applied to the transmission infrastructure in potential follow-on phases.

5.2 Concept Description

The ***GasNet***TM system concept our development team started with, is shown in Figure II-3 and Figure II-4 on page 13, which depict the installed system 'tapped' into a pipe with its installed electronics/batteries and above ground interface port (I.1a); up-close details of the preliminary pressure/flow/moisture/etc. sensory-modules (I.1b); depictions of such installations in a typical urban setting during an excavation and third-party interaction situation (I.2a); and a potential operator feedback screen provided through remote computerized processing at a utilities' central control station (I.2b). The overall system consists of an in-the-field keyhole-installed unit with an in-pipe sensor and processing module, and a buried power and access-port unit at ground level. The sensor module is installed into the pipe by way of a standard field-installed fitting. Inside the field-fitting, resides a sealed and removable sensor wand, which contains the main sensory elements. For illustration purposes, we are depicting a radio-wave transmitter at the tip of the wand, a set of flow-passages for a hot-wire anemometer flow-measurement system, a multi-channel acoustic-level sensor, and multi-planar micro electromechanical systems (MEMS) based pressure and methane-composition sensors atop the main body of the sensor. The flexible joint allows the wand to flex out of the way should equipment need to pass the location (repair or inspection from within the pipe for instance)[1]. The sensor power and data-lines are run to a local embedded processing system, which reads, filters, scales and processes the data. Real-time communication of the data-set back to the central control station is accomplished via a local radio frequency (RF) transmitter board-set that packages TCP/IP, (Task-Control-Protocol) encodes and transmits the data via the antenna into the pipe-space. The data is picked up by the next transmitter, and re-sent in a relay-node mode until it reaches the control-station receiver. The data is then identified with respect to transmitting origin and decoded and displayed/logged at the local control-station. Since communication is over a a standard interface, all other existing systems owned by the utilities can be interfaced to the new console-system.

The ***GasNet***TM system was also conceived to be able to track and monitor third party activities. One method would use embedded vibration (accelerometer) and acoustic (microphone) sensors to pick up above-background signals to warn the utility in real time of the presence and location of the disturbance (digging backhoe impact or displacement). The supervised approach would involve

1. Since the sensors and antenna are elevated immersion in water/oil is unlikely and contaminant-deposits are also highly unlikely due to cleanliness of todays' natural gas

giving a contractor access to the lid-protected interface. The contractor would then plug in a special connector or flip a hard-wired switch. This in turn would signal to the central control station of ongoing activity in the area. If authorized, the sensors surrounding that area could be monitored as to flow and pressure, to assess the potential for breaching of the line. In addition, the contractor might choose to apply an AC-current between two such sensor locations bordering the planned work site. It would also be feasible to use a single sensor-location, with a return cathode rammed into the ground (to close the current loop) slightly beyond the work area. Once tied into the pipe this way, a simple passive electromagnetic (EM) field detector, on the excavation equipment or manually deployed hand-equipment, would sense the AC-induced magnetic field emanating from the pipe. This signal would then be used to warn the contractor as to presence (binary signal) and closeness (analog field-strength) to the pipe, without any costly *a priori* site-mapping (such as with GPR) or costly real-time sensor-hardware.

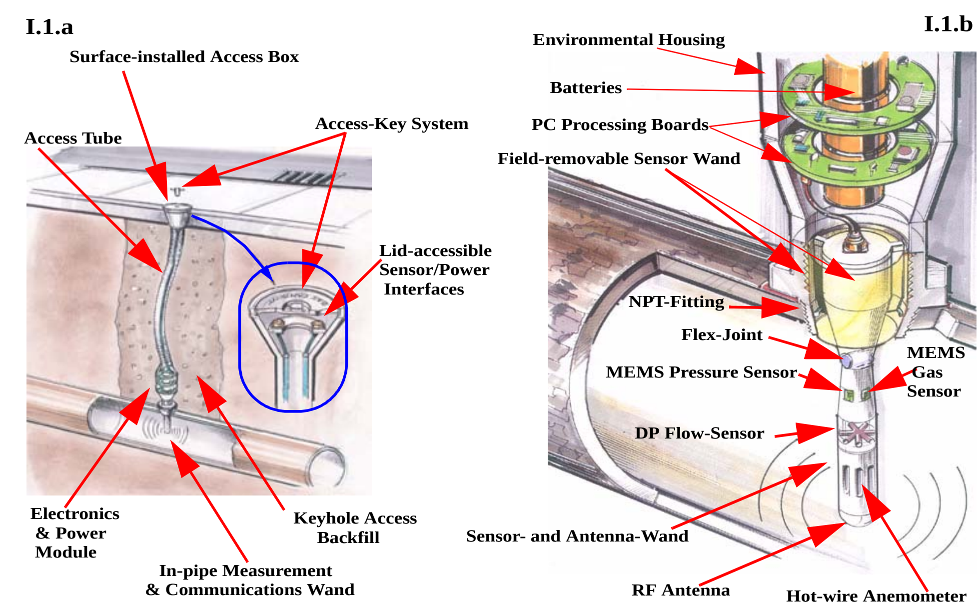

Figure II-3: Overall ***GASNET™*** system concept: Sensing-, RF-Communications, Computing- and Power System with an Installation View

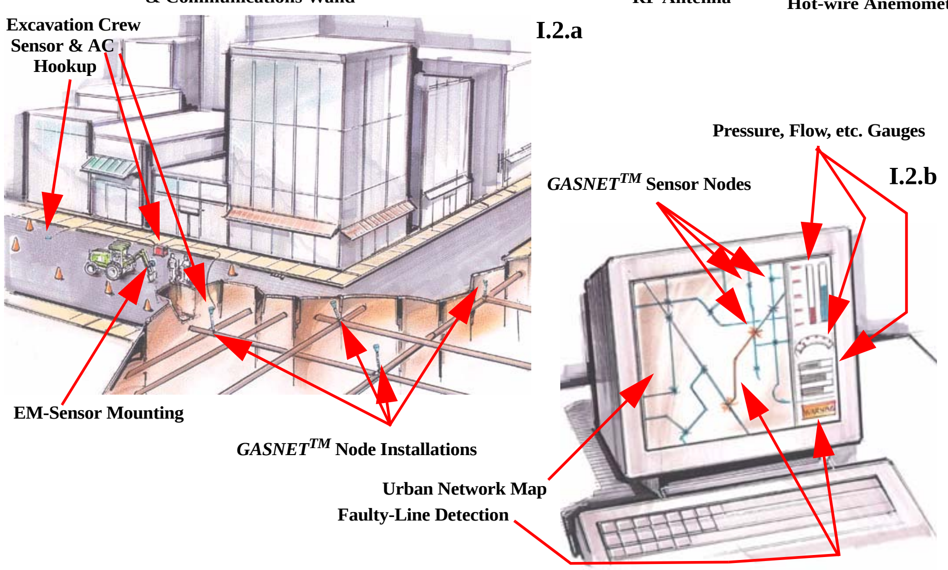

Figure II-4 : Overall ***GASNET™*** system concept: Urban Deployment & Operator Console Interface

6.0 System Design Description

The ***GasNet™*** system, consisting of the pipe-internal sensor-wand, safety-housing and power-supply, as well as the remote graphical user interface subsystems are described in more detail in this section. This section is laid out to address the overall system layout, and then delve into each subsystem in more detail.

6.1 Overview

The entire system design, as visualized through CAD renderings, was made up of the pipe-internal sensor wand, the external safety enclosure housing the electronics, the off-board power supply unit, and the remote user interface. A depiction of this system architecture is shown in Figure II-5:

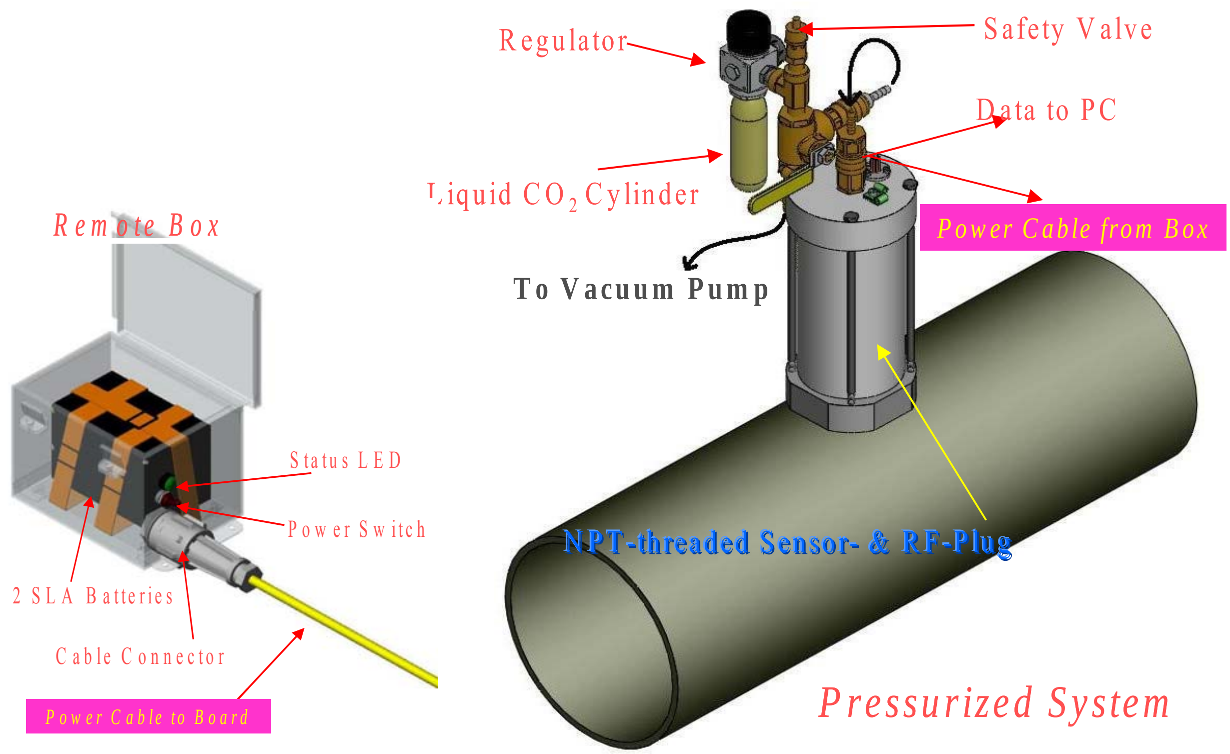

Figure II-5: ***GasNet™*** System Overview - CAD

A final assembly view with shipping protector is shown in Figure II-6:

Figure II-6: ***GasNet™*** system assembly view ready for shipment

6.2 Sensor-Wand

The sensor-wand itself consisted of a single PCB, which was potted in a machined NPT fitting. The different elements and main sensor elements were laid out on the sensor-wand in the proper locations. A diagrammatic overview of the wand and its associated sensors, can be see in Figure II-7.

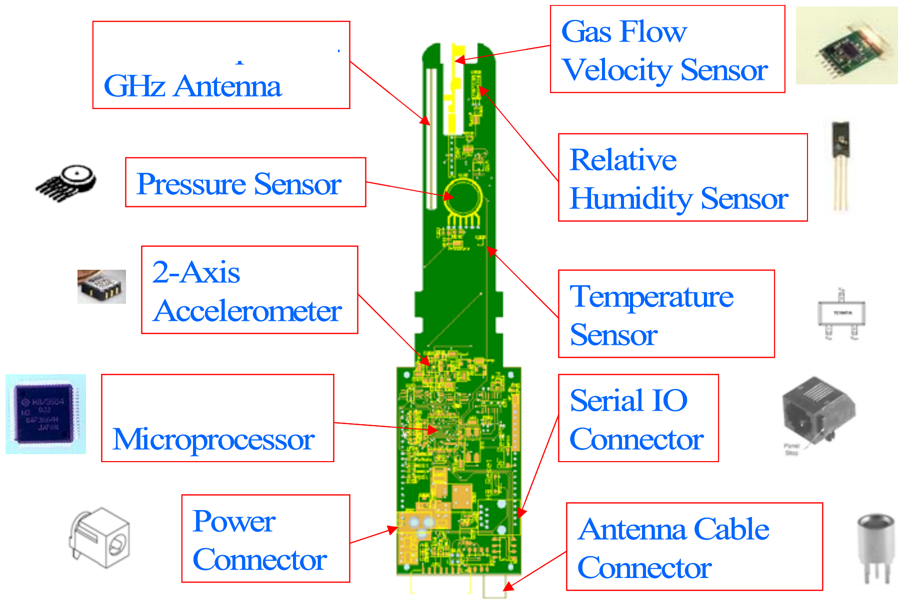

Figure II-7: Sensor-wand design and associated sensor layout

In order to accommodate several pipe-diameters, and to ensure that the gasflow velocity sensor would reside at the centerline of the pipe, the board was designed with break-off notches so as to allow for proper alignment during potting operations into the stainless NPT-plug.

The electronics were based on a simple architecture, relying on a dedicated microprocessor to poll all the sensors on the wand, while interfacing to the wireless RF-electronics over a simple serial-cable with a pre-established protocol. The diagrammatic depiction of the simple architecture is shown in Figure II-8:

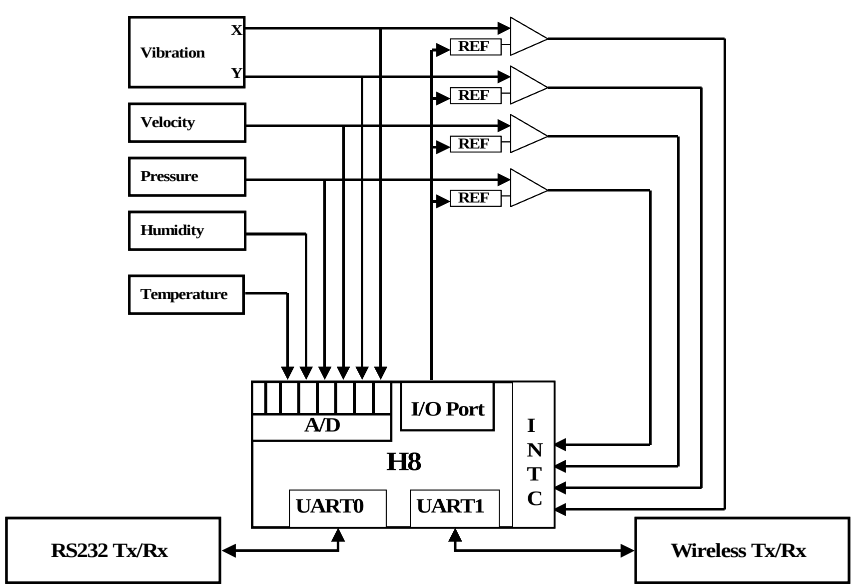

Figure II-8: Simplistic block-diagram of electronics architecture

The wand-PCB when fully populated and assembled is shown in Figure II-9:

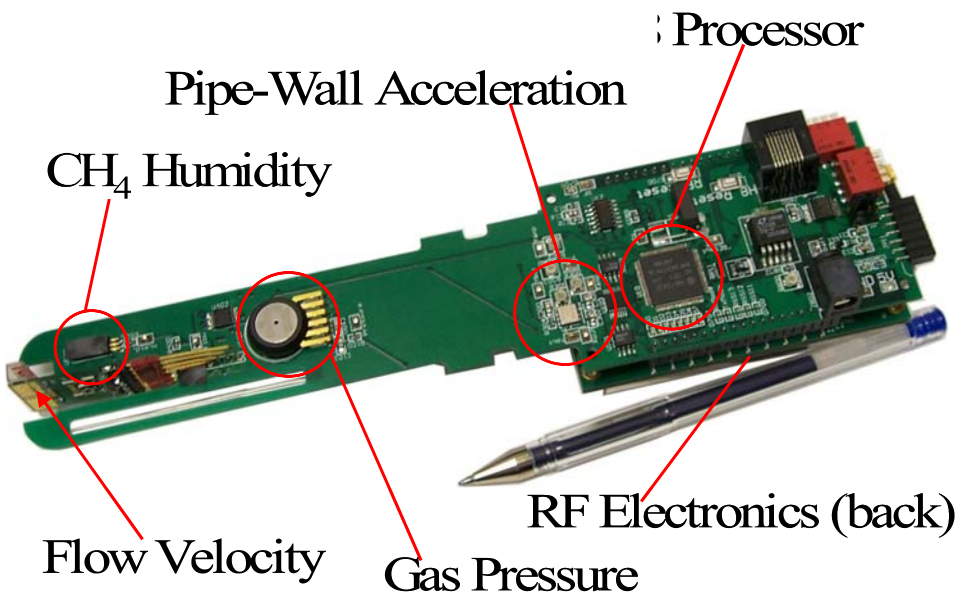

Figure II-9: Populated sensor-wand PCB

A finished (populated and potted) sensor wand is shown in Figure II-10:

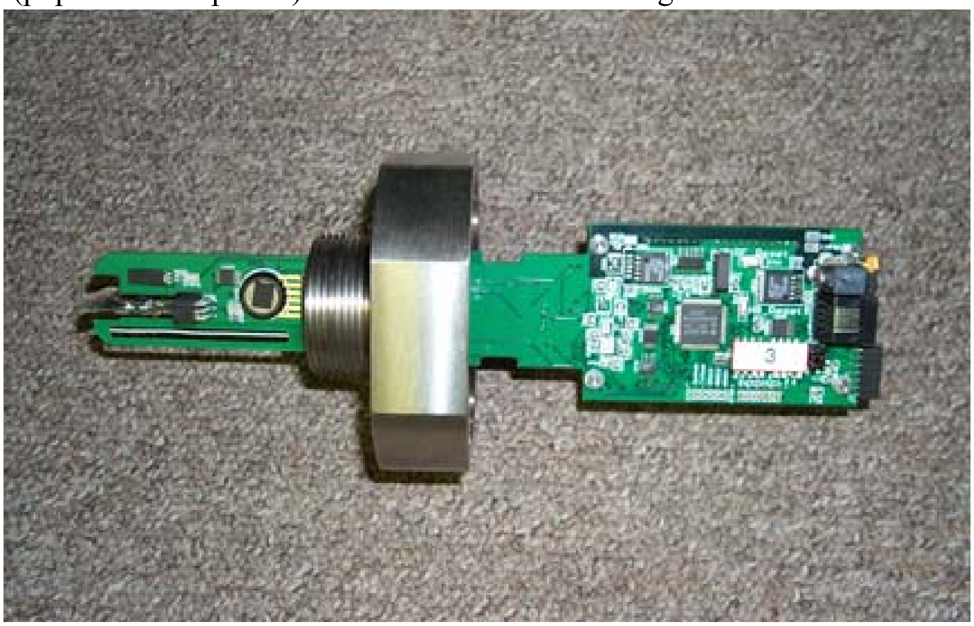

Figure II-10: FInished (populated and potted) NPT-fitting Sensor wand

6.3 Safety Enclosure

The safety enclosure that was developed to connect to the NPT-plug was not only for protective use for the PCB, but also for operational safety. The procedure that was required by the utilities to be followed for installation and operation, required that all non-certified electronics be purged and pressurized with a non-oxygenated gas. The approach we employed utilized a vacuum-pump that would evacuate the sealed electronics enclosure down to 1/10 of an atmosphere, after which a pressurized CO_2 cartridge would deliver inert gas into the enclosure through a regulator set to several psig above pipe-internal pressure; this state was preserved and monitored while the unit was powered up from the remote battery unit. A picture of the sealed housing, endcap, NPT-plug and associated safing gas-assemblies is shown in Figure II-11:

Figure II-11: Safety Enclosure Unit

6.4 Power Unit

The power subsystem consisted simply of an enclosure with OEM NiCad battery cells wired in parallel to allow for week long field-trials. The unit had a simple power-on indicator and a sealed on/off switch. The unit was connectorized using a screw-on sealed connector pigtail with a 30-foot long power-cord to allow it to be remoted from the excavated pipe and hole during field-trials. An image of the battery enclosure is shown in Figure II-12:

Figure II-12: Battery power enclosure with cabling

6.5 Graphical User Interface - GUI

The GUI (Graphical User Interface) was developed based on the premise of displaying a single unit's data in a large graphical form-factor, while having the data for others readily available and being able to switch which wand was being displayed at will. The implementation was carried out under ***LabView^{R}***, in order to maximize flexibility during testing, even if sacrificing system performance and throughput. A screen-capture of the final GUI layout is shown in Figure II-13:

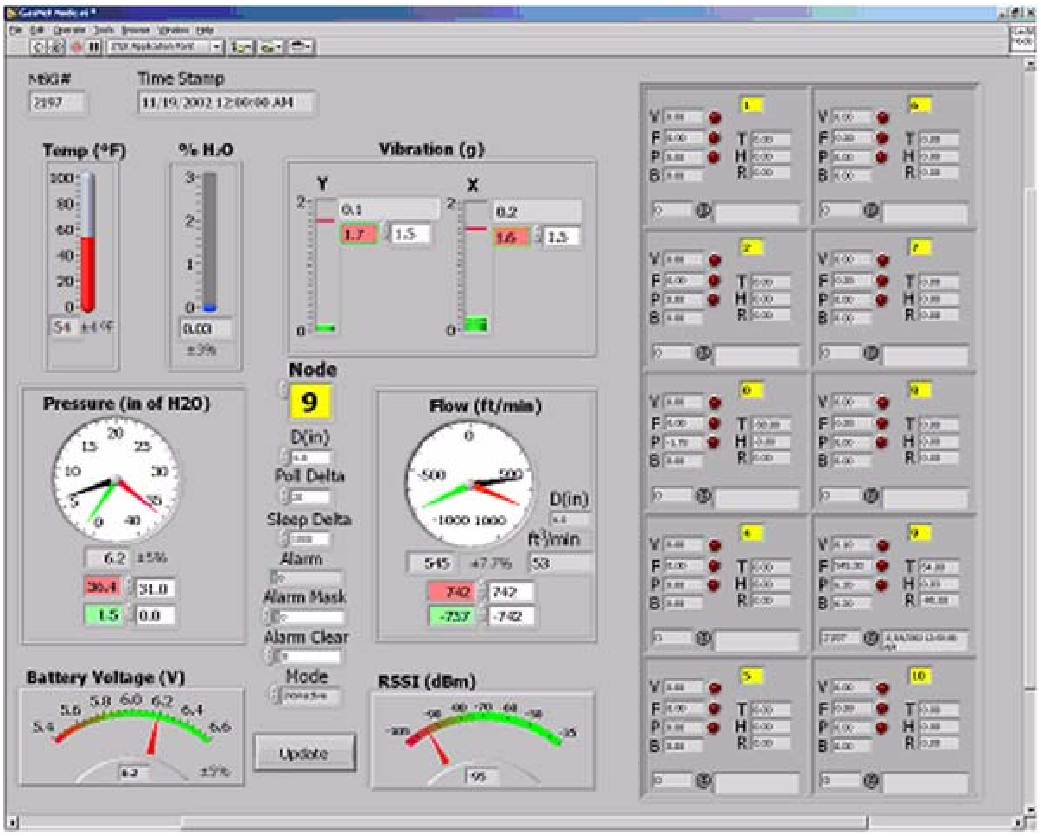

Figure II-13: Final GUI screen-capture layout

6.6 Software Architecture

The software resides on an H8 micro controller which runs custom firmware to interface to pressure, velocity, relative humidity, temperature, 2-D accelerometer, two serial communication devices and digital potentiometers. The digital potentiometers are set up to provide voltage thresholds for providing 'alarms'. One serial port (local) is connected to an RS-232 transceiver, while the second port (wireless) is connected to a wireless transceiver unit running its own proprietary software.

On-board configuration switches define each unit's ID number and master-slave designation. In the Phase I implementation, the system was designed for only one master in the network and all node ID numbers had to be unique. Firmware programmed into the H8s differed slightly depending on the master/slave designation of the node. Master nodes were set up to copy messages from the local serial port to wireless and vice versa, thereby allowing a datalogging hook-up while also serving as a relay node. In this manner, the master relays all messages between a user interface and the rest of the nodes in the system.

The H8 firmware implements three different work modes: one special work mode state, and two configuration modes. Different work modes are defined to allow different levels of power conservation and interactivity of the system. The flow chart in Figure II-14 captures the operation of the firmware in different modes in a single image (configuration modes allow user to configure and run diagnostics on the node).

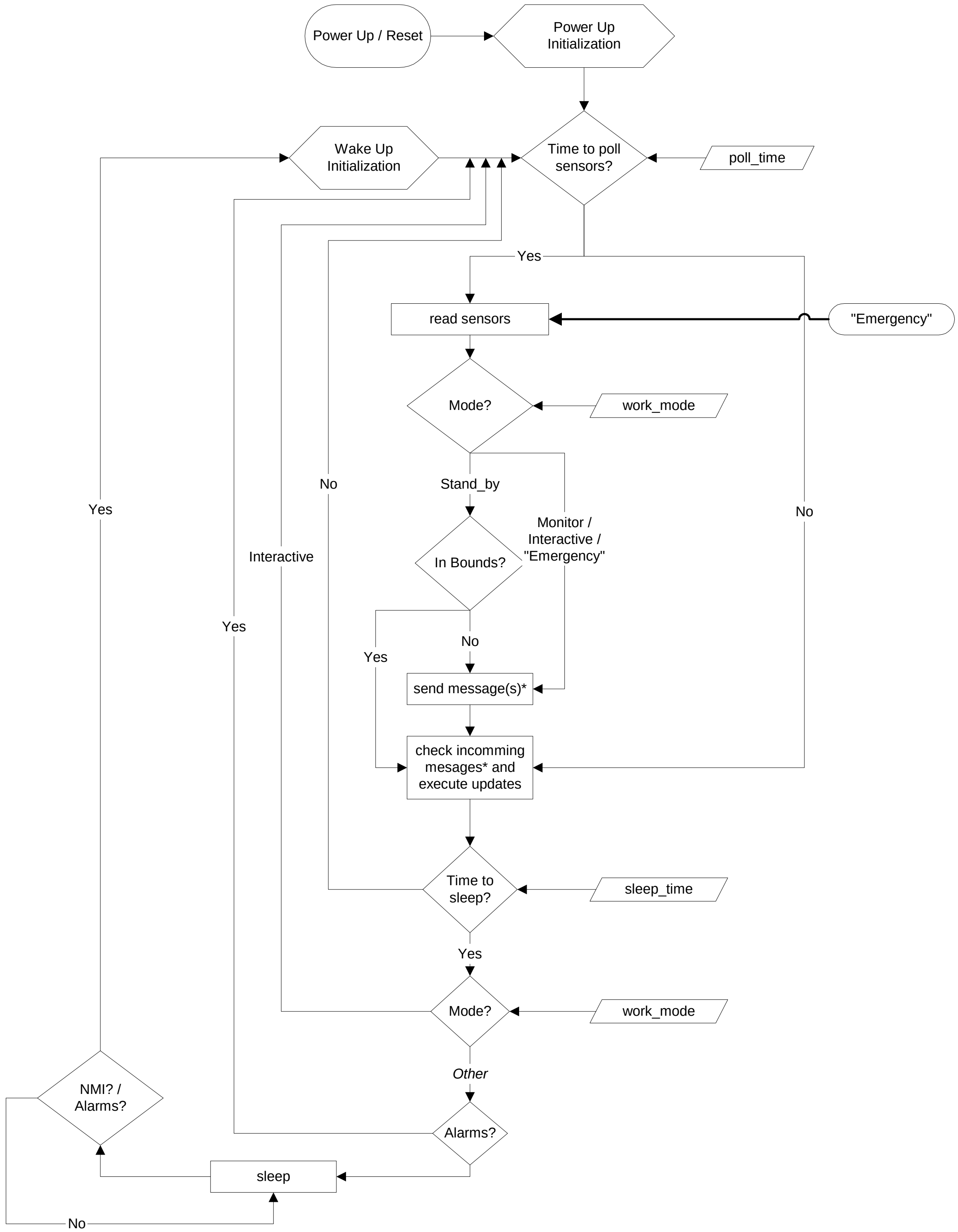

Figure II-14: Software mode flow chart diagram

A more detailed description of the modes can best be detailed as follows:

- **Work Modes**

  Interactive mode keeps the system continuously running without ever going into a hardware power saving sleep state. This mode is useful for continuous monitoring and reporting of the gas main conditions.

  Monitor mode is useful for periodic checking of the gas main conditions. In this mode, after reporting the data, the node goes into a sleep state for a user-defined period of time.

  Standby mode uses user-defined upper and lower bounds for each sensor. In this mode, the node will behave just like it does in the Monitor mode except the data is only reported if any of the sensors' readings falls out-of-bounds.

  The node enters an Emergency state while in any of the work modes, if one of the hardware alarms is triggered. Emergency state wakes-up and prevents the node from going into sleep mode until the user deals with the alarm conditions. When the alarm disappears, the node returns to the previous work mode.

- **Configuration Modes**

  Transparent mode allows the user to configure wireless modem settings using a local serial port. Once the user exits this mode the system returns to the previous work mode.

  Self-test mode performs a diagnostic on internal sensors and prints results to a local serial port. Once the diagnostic is finished, the system returns to the previous work mode.

7.0 Experimental Results

This section details the experimental activities in Phase I of the program. The activities relate to the laboratory and field-trials, and specifically to calibration and field-data gathering.

7.1 Laboratory Testing & Calibration

The laboratory setup was used to test the functionality of the system as well as calibrate most of its sensor systems. The setup consisted of a simple 6-inch steel pipe-loop with bolted flanges. Internal honeycomb sections were inserted in order to straighten the flow of an internal fan used to generate flow-speeds of air at various pressures. Flow and pressure were measured by independent sensors (digital pressure-gauge and hot-wire anemometer). The sensor-wands were all tested in this loop and calibration curves generated for each and stored on the display computer to allow for the acquisition and representation of accurate field-data. Accurate extrapolation[1] was possible though the use of comparative densities and other physical variables published in the literature. An image of the test-setup and an in-process calibration situation are shown in Figure II-15:

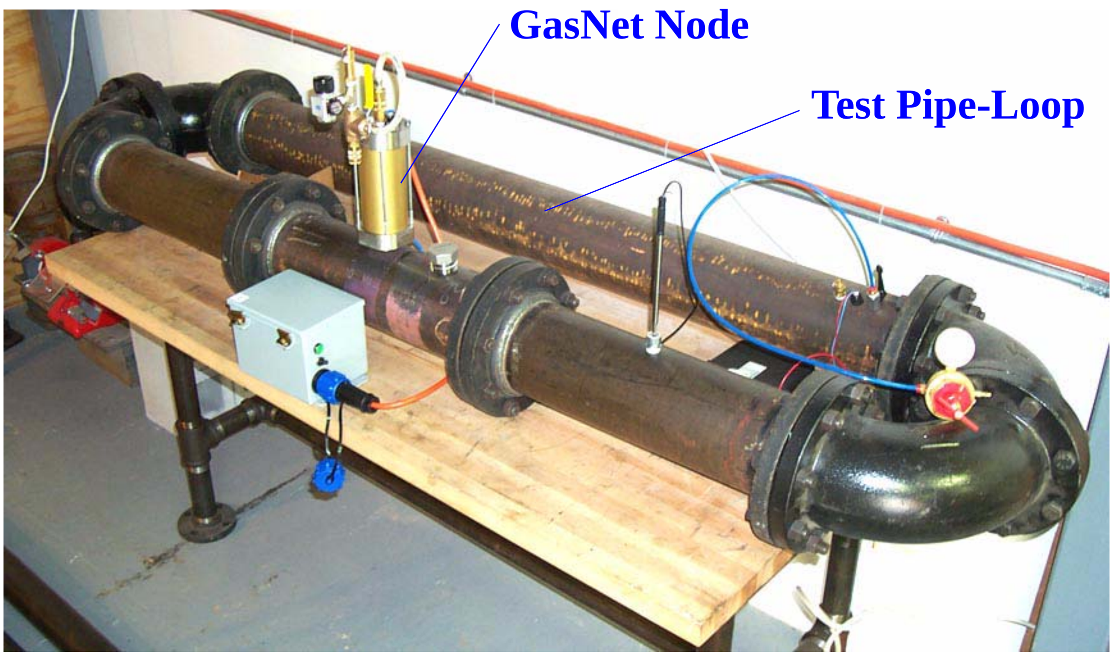

Figure II-15: Laboratory testing and calibration pipe network setup

1. necessitated by the fact that compressed air was used for calibration, rather than compressed natural gas

7.2 Field Trials

7.2.1 Setting

Field trials were jointly carried out with Keyspan Energy, Inc. in West Valley, NY, a suburb of New York City on Long Island. The test area was selected due to its frequent issues in winter months (low water-table) and the impending repair of said section. The selected mains were all 6- and 8-inch diameter and were all cast-iron (CI) with bell-and-spigot inner-sleeve joints. An image of the setting location is shown in Figure II-16.

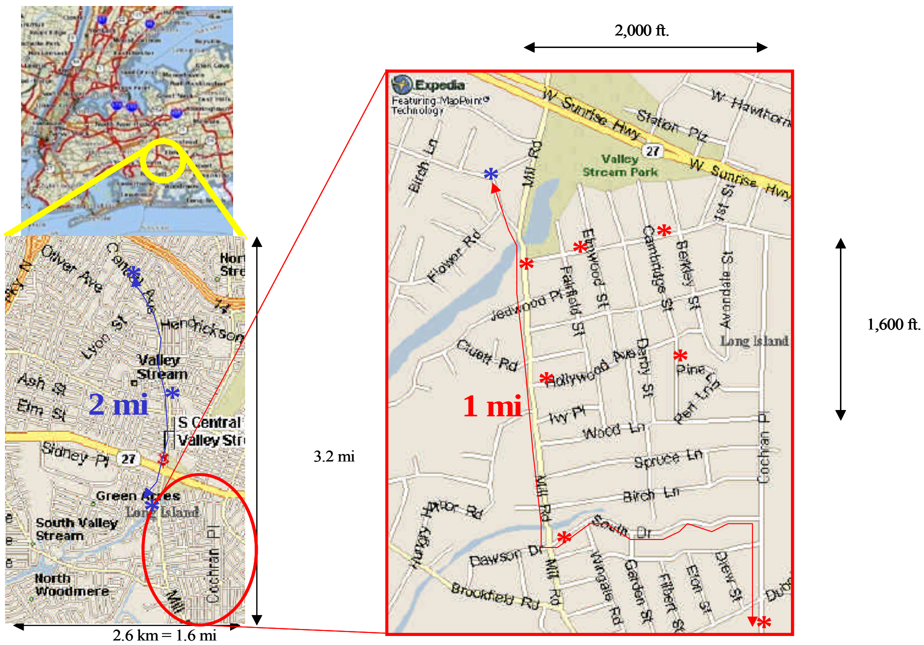

Figure II-16: Field trial setting on Long Island, NY

The setting involved a total of 10 sensors-units distributed across a 1/2 square mile area of distribution mains, as well as a linear 1/3 mile section of main along a single main feeding distribution sidemains. The purpose was to collect data for a distributed spider-like distribution setting, as well as a linear pipe-run and compare the efficacy of communication and data utility. An image of the locations for the spider-network are shown in Figure II-16, while the location of the linear-pipe sensor-units is shown in Figure II-17:

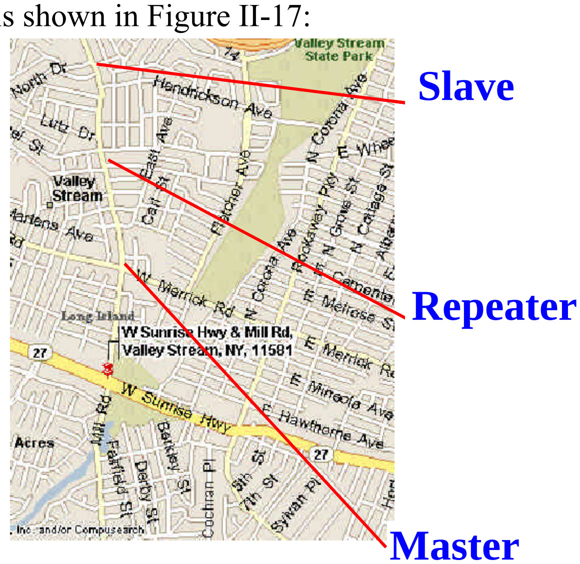

Figure II-17: Sensor-installation locations map

7.2.2 Setup

The setup for the sensor and communication system was fairly straightforward. Through the invaluable assistance of the local utility Keyspan, Inc., all the required excavations were made in the lowest-cost locations wherever possible. The installation and safety process was carried out by trained and certified utility personnel, with the contractor providing to the installer(s) only the training necessary to avoid damage to the units during installation and removal.

The excavation of the necessary 4x4 foot and about 3 to 4 foot deep holes was carried out prior to the contractor team showing up. Once on site, the installation was fairly quick and simple. All 10 sensor-pods were installed within a single 8-hour period, and ready for data-collection and experimentation on the second day of field-trials. A complete step-by-step pictorial rendering of the process, is shown in Figure II-18:

Figure II-18: Step-by-step process of ***GasNet*TM** installation and operation

7.2.3 Data Collection Overview

The data collection process revolved primarily around selecting a single node as the ‘master’ data-collection node, with all other nodes sampling local sensors and sending their data wirelessly under a proprietary messaging protocol to the master node - at this location the data was time-stamped, scaled and logged for later analysis.

The data-logging ran into a major problem right out of the gate. None of the spider-network deployed sensors were able to talk to the master node except for one single node. Upon careful review of full-scale sized ‘plates’[1], it was found that in each of the salve-master communication paths, was located a drip-rod in the pipe[2]. These drip-rods act as a radio-frequency ground, in effect terminating all communication signals. The spider network of sensors was thus incapable of delivering any data to any slave-master combinations given the pre-determined hole layout. It was then that the contractor and utility teams decided to concentrate on the linear feeding gas main hole setup, where all nodes were located in a single main along a main road, without any drip-rods. In

1. Plates are referred to by the gas industry as planar layouts of areas showing streets and residential tie-ins on a grid network in a scale sufficient to show as built detail. Large areas are broken up into multiple plates, where each plate fits on a full-size D-sheet of paper (typically).
2. Drip-rods are vertical hollow rods in low-points in a main, allowing for the pumped/suction removal of water accumulated in a low-pressure distribution gas main.

addition, it was found that the only two talking nodes in the spider-network had substantial RF signal-attenuation, seemingly limiting the node-to-node communication range to around 1,200 to 1,500 feet (max.). Based on this empirical evidence, and the determined hole-separation, it was decided to utilize a master/repeater/slave configuration to maximize total signal travel distance.

In this setup, as shown in Figure II-17 on page 22, the master was selected as the southernmost receiver, with a repeater further north, and a slave in the northernmost location; the maximum distance between nodes was around 1/2 mile. The use of a master/repeater/slave configuration proved successful, as right after installation it was determined that all units were successfully communicating. It was at this point and over the next 1.5 days of field-trials, that valid field-data was collected by the contractor field team.

7.2.4 Data Types and Samples

As part of the utility-selected variables to be measured, the contractor was able to successfully collect data from almost all sensors in all locations. The data-types and sample data logs are explained and elaborated upon in this section below.

- **Gas Flow Speeds & Flow Rate**

  Probably one of the most interesting variables for the utilities revolves around the flow rate of the gas in the mains. The sensor utilized measured only flow-speed, and needed to be converted to flow-rate based on an iterative procedure to determine flow-type (laminar or turbulent) and then flow-rate based on the knowledge of sensor-location, pressure, density, etc. Flow-speed was thus collected, interpreted and flow-rate deduced from the same. A typical flow-speed plot is shown in Figure II-19:

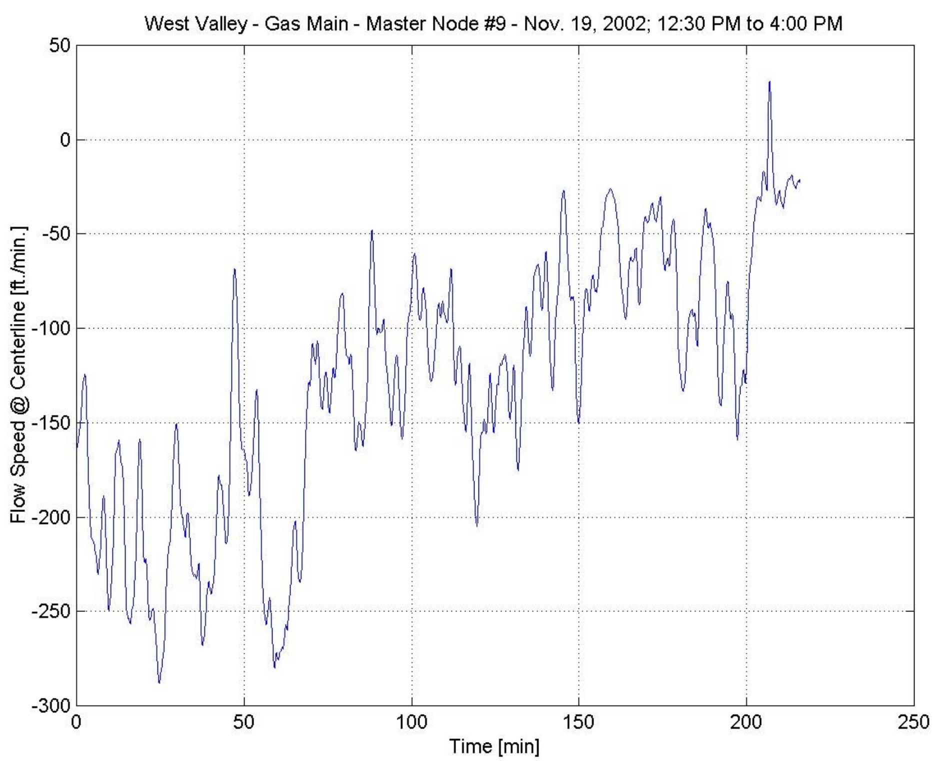

Figure II-19: Typical gas main flow-speed data-log plot

Notice how the flow-speed varies as a function of time, almost reversing direction (N to S); note also the seemingly oscillatory nature of the flow about a slower-frequency variable flow-speed. If a different day and location within 1/2 mile is selected, the computed flow-rate (a scaled variant of the flow-speed plot), would reveal even more interesting behavior, such as that shown in Figure II-20:

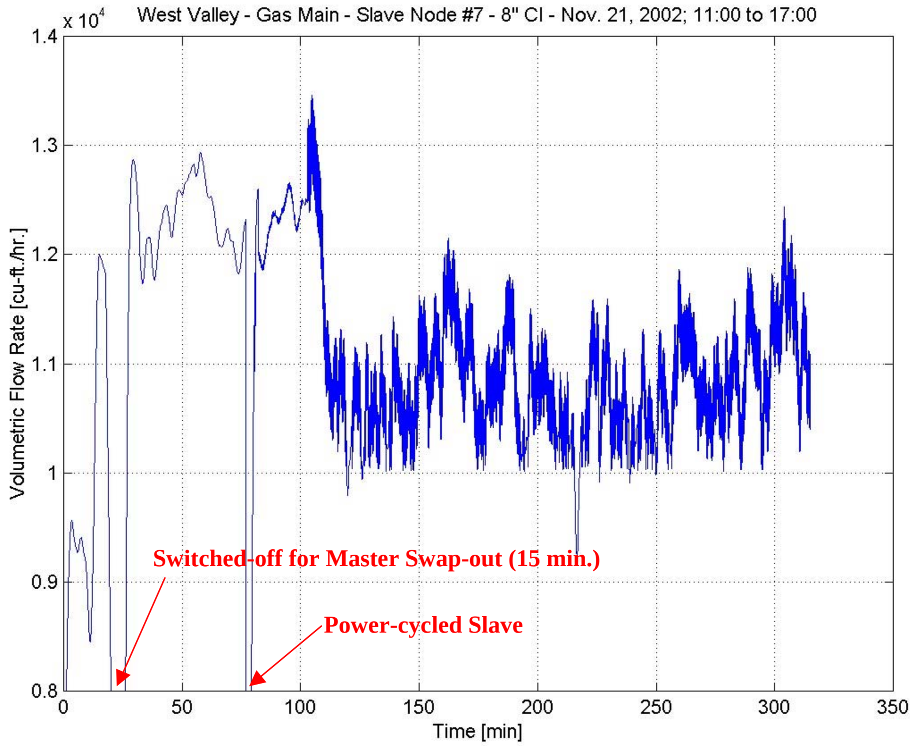

Figure II-20: Flow-rate in a gas man - data-log plot

It is again noteworthy that the flow seems to have a cyclical/sinusoidal behavior to it, except that at this location the flow varies far less in magnitude and direction than the one shown in Figure II-19 on page 24. The seemingly higher-frequency dithers can not be attributed to measurement noise (see earlier data with far smoother data); a closer look with expanded time-scale also reveals that these 'dithers' are superimposed higher-frequency variations in flow.
This data-set reveals some of the more interesting behaviors of gas main flows. Since most utilities use static worst-case Stoner-model data to design and understand their networks, it is very significant that flow-speeds measured at this location are very variable, time-of-day dependent and of a cyclically/sinusoidal nature - a clear indication that the gas distribution network indeed displays some interesting 'live' behaviors.

- **Gas Main Pressure**

Unfortunately, gas main pressure logs revealed that the sensor mounting suggested by the manufacturer of the pressure sensor was not rugged enough to ensure proper sealing. As a consequence, pressure-data was only available for a very short period of time, before it would degrade and the sensor equilibrate to the in-pipe levels, giving an effective long-term zero-pressure reading for the main - this effect is shown in a typical data-plot in Figure II-21 on page 26.

Notice how the main pressure of slightly above 5 in-H_2O degrades rapidly to an offset net-zero value - according to the utility, the 5+ in-H_2O is about the pressure they expected to see.

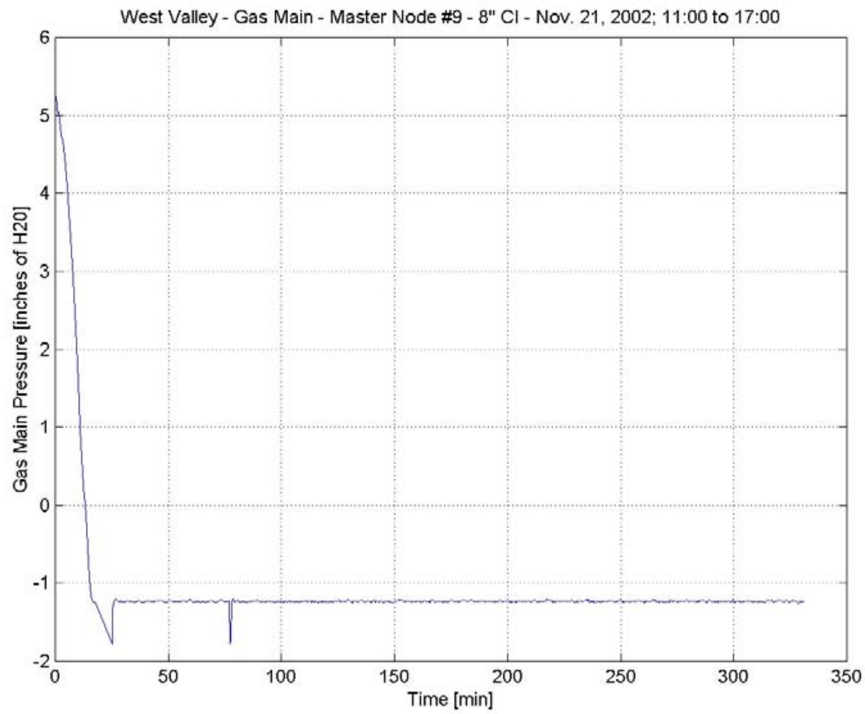

Figure II-21: Gas Main Pressure - Representative data-log plot

• **Gas Water Content**

Another interesting variable utilities wished to have monitored was the net water-content of the gas as expressed in percentage by volume. This measurement was affected through a relative humidity sensor with a numerical conversion to water content. A typical log for the site is shown in Figure II-22:

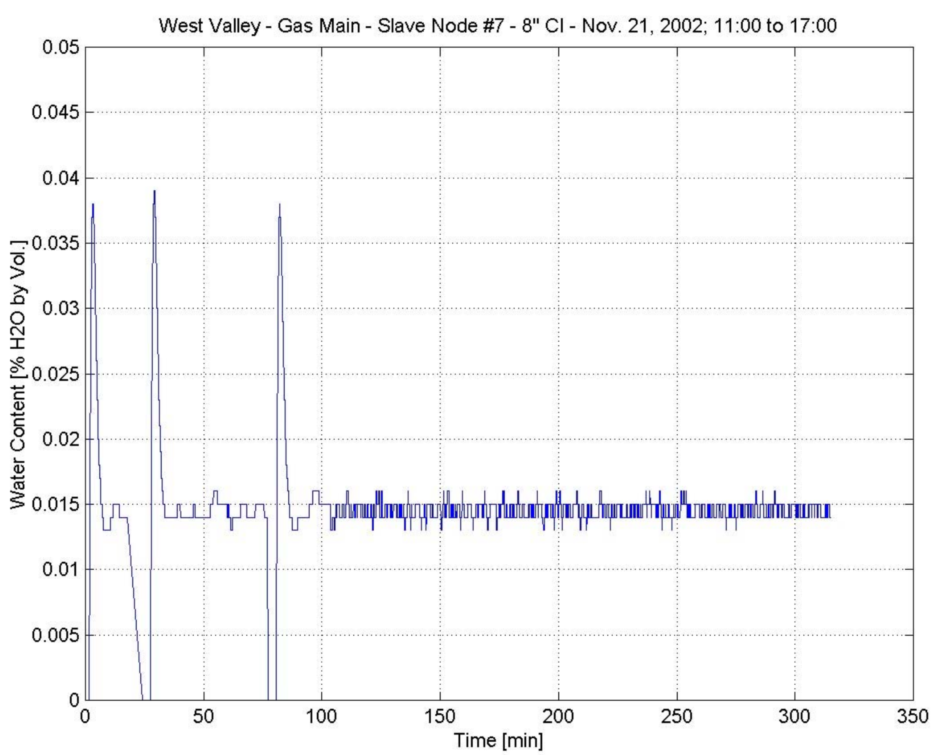

Figure II-22: Gas Main Water Content Data-Plot

As expected by the utilities the water content was steady and rather low (0.015% by volume), implying the gas was dry and thus containing saleable BTU-content for the customer.

• Gas Temperature

In order to perform several calibration and computations to arrive at related values, it was important to measure temperature of the gas. Since this variable thus came for 'free' it was deemed interesting to the utilities to monitor this variable, not from a process or billing perspective, but rather from a variance-over-time. This is important as utilities believe that leaking bell-and-spigot joints could be due in colder regions due to the freeze-thaw cycle, which in turn should be observable as a temperature cycle over time; this relation should thus depend on the ambient temperature, and both values should be plotted. Since the field-trial is only a snapshot in time, rather than across seasons, it is only provided here for reference purposes and to demonstrate that it can be done rather easily. An image of temperature log for the selected site is shown in Figure II-23:

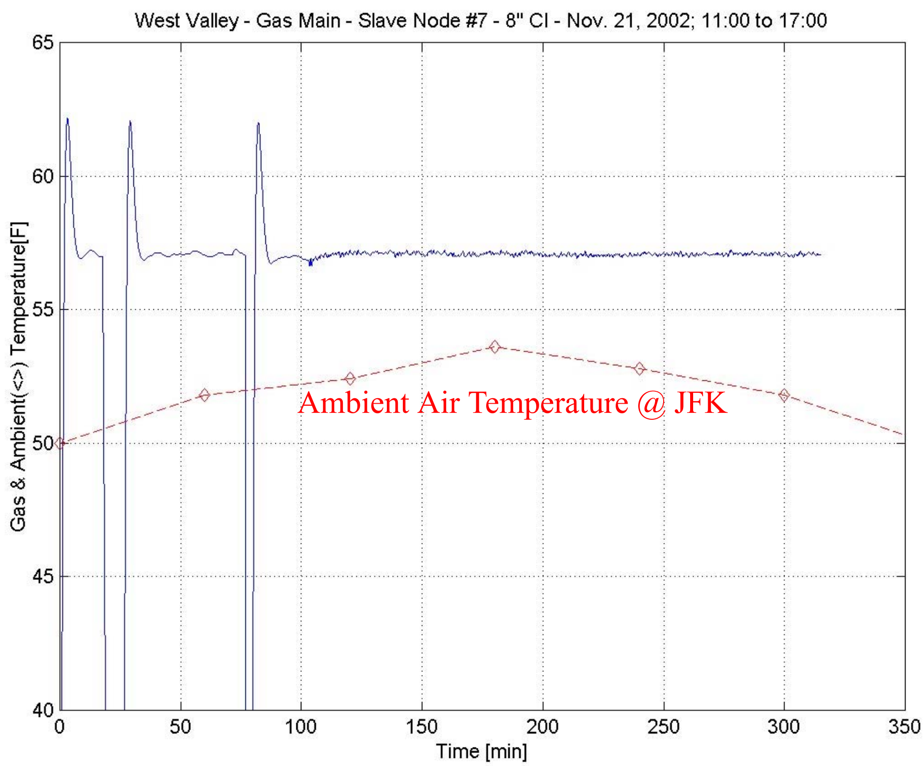

Figure II-23: Temperature data-log - gas main and ambient

Notice how the temperature (despite the spikes due to on/off power-cycling) stays extremely constant over time (several hours), despite ambient temperature fluctuations. This variable would need to be monitored over at least several seasons and then plotted before any trend analysis would render usable conclusions.

• Gas Main Vibration

Utilities were interested in knowing whether external excitation (road-traffic, excavator digging, etc.) would be detectable by the sensor wands inserted into the pipe-wall. Towards that end a dual-axis accelerometer with 2g measurement range was potted into the fitting that screwed into the pipe and its out put monitored under natural and simulated conditions. As the plot in Figure II-24 on page 28 shows,

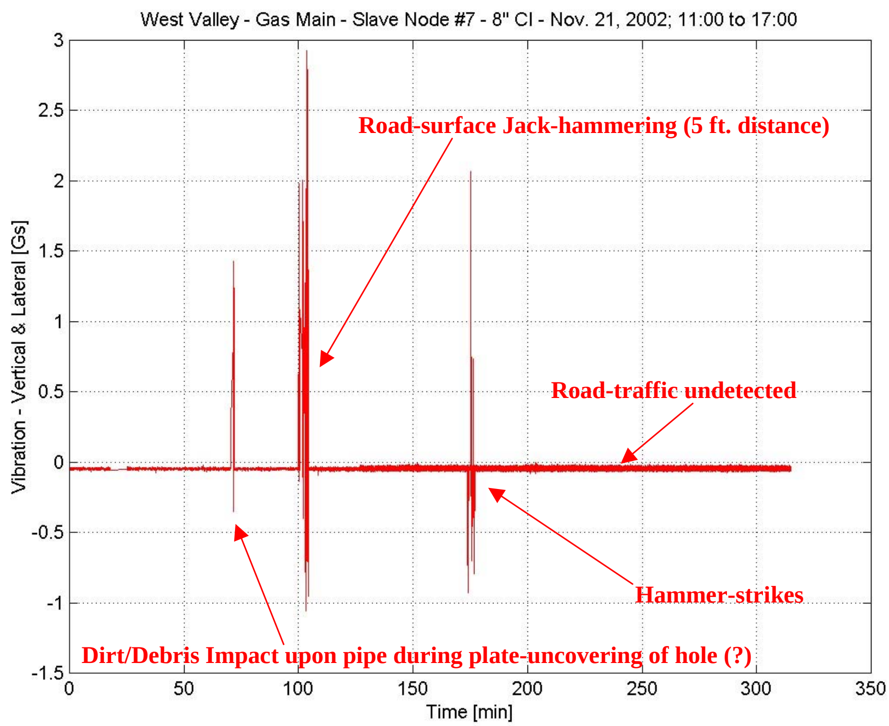

Figure II-24: Gas Main pipe-steel shell vibration response to external excitation

certain types of excitations are locally detectable. Road-traffic was found to not be a detectable influence, but jack-hammering above the pipe within a certain distance did indeed set off the sensor in a readily measurable way. Additionally, if the pipe was struck by a metallic object, in this case a hammer simulating a backhoe strike, detection would be rather straightforward as well (it is however seemingly impossible to differentiate amongst these two).

The main caveat on this experiment is that the data shown in Figure II-24 only refers to the segment of cast-iron pipe the sensor is attached to. Measurements taken at sensors 1/4 and 1/2 mile away were not able to register these disturbances. It is thus noteworthy that if a monitored section of cast-iron pipe is subjected to these type of disturbances, it will be readily detected. The question of how far this signal would travel through the bell-and-spigot joints (to be seen as attenuators) before a sensor could no longer measure it is unclear. Instrumenting every section of (20 to 3 feet) cast-iron pipe to safeguard against third-party damage also seems unrealistic. It thus seems to indicate that this method would only work well in higher-pressure steel mains were pipe-sections are welded/bolted and more readily transmit vibrations through the pipe-wall (to be tested in Phase II if approved). For the case of cast-iron pipes, it will most likely require a pipe-internal acoustic monitoring system, which is independent of the pipe-wall joint-connection, but only cares about the transmission from the pipe-wall into the gas stream (jack hammering and excavator bucket-strikes) - this also will only be investigated in a later follow-on phase.

7.2.5 Data Evaluation Summary

Based on the data collected and the on-site evaluation of the data-validity and -trends, the following summary observations were made (in no particular order of importance) by the AI contractor team, which were corroborated by the on-site utility representatives:

1. Maximum ranges of $^1/_4$ mile between adjacent nodes for a 1W RF-system were found to be much lower than the ranges measured in steel-pipe test networks. This leads us to conclude that joints have severe attenuation on the signal, due to their lack of electrical conductivity (or at least high-resistance); drip-rods were again found to be RF-grounds, killing any RF

propagation in a particular section of pipe.

2. The gas flow behavior was noted to be the most interesting in terms of its dynamics and temporal behavior, which can not be extracted form a Stoner model and could possibly reveal important trends.
3. As expected, the water-content of NG these days is very low, and found to be well below 1% by volume.
4. Despite failure of the pressure sensors, preliminary data seems to indicate that pressures are along nominal lines, even though their dynamic behavior would be of interest to understand in the future.
5. Temperature was as expected fairly steady, but its longer-term behavior though an entire winter-season would be valuable to log and understand, to better understand potential leakage-contribution due to freeze/thaw induced motions at the bell-and-spigot joints.
6. In retrospect, vibrations due to mechanical pipe-wall oscillation, can only be expected to be picked up in the near vicinity of any rigid pipe-section making up what is essentially a segmented pipe-network in the case of cast-iron. Hence only local phenomena can be observed, which is expected to improve radically should welded/bolted steel pipe-networks be instrumented.
7. Overall the data contained far more dynamic behavior with unexpected trends and oscillatory behaviors (flow) than would have been expected.

8.0 Summary

The Phase I development effort for a proof-of-concept ***GasNet^{TM}*** system can be deemed to have been very successful overall. The main technologies, ranging from sensing, communications, software and display to in-filed installation and safety design were shown to be feasible. The selected sensors and the local microprocessor system were shown in the lab and field to perform as expected. The wireless communications link was also shown to work in a dynamic network setting, with varying operational modes implemented in software (emergency, monitor, etc.). The user interface, even though rudimentary in this phase, was commented upon by utility representatives as being extremely usable and very informative.

Experimental field-testing showed gas flow rates to exhibit highly dynamic and oscillatory behavior varying widely across even a $^1/_2$ mile stretch in terms of amplitude (flow-rate) and flow-direction as a function of time-of-day. Limited pressure measurements showed that pressures were in the statically-predicted range, yet dynamic behavior was not measurable due to premature sensor-failure. Gas temperature and water content were found to be extremely steady, with higher temperatures of the gas flow than ambient, and independent of daytime temperature fluctuations; water content was extremely low and measured at less than 1% by volume. Mechanical pipe-wall vibration measurements proved to only be possible within the vicinity of an instrumented pipe-section due to the segmented and isolating nature of the cast-iron bell-and-spigot design; measurements did however show that road-traffic could be ignored, while road-surface jack hammering was readily detected, as were impact-loads as small as a hammer-strike on the pipe-wall.

There were some minor setbacks in the operation of large number of sensors due to the proliferation of drip-rods (which reduced and even eliminated RF-communication links thereby voiding the ability of setting up a pipe-internal wireless network), but overall the concept of live in-situ data gathering, communications and -collection was successfully proven. The decision to test in cast iron mains due to the reduced complexity and cost of field-trials, resulted in a diminished wireless range due to excessive losses in a segmented pipe-network with poorly-conductive bell-and-spigot joints; however we feel this will not be the case at all when welded/ bolted medium- to high-pressure distribution mains will be instrumented in succeeding phases.

Utility representatives commented at the conclusion of the field-trials that would have other uses in low-pressure cast-iron mains beyond those of a shorter-range data-gathering and -monitoring system; proposed uses included (i) the use as a Stoner-model validation tool through measurements over space and time at critical locations, and (ii) use as a capital-project planning tool by serving as a wired/autonomous data-logger to better support engineering decisions

9.0 Conclusions and Recommendations

Based on the Phase I results, the following conclusions were drawn by the AI contractor team in different areas:

• Sensing Systems

- *Flow-rate measurements based on flow-speed are extremely valuable and can be accomplished with a flow-speed sensor.*
- *Temperature and humidity are 'flat-liners' but would need longer-term monitoring to determine their utility.*
- *Vibration monitoring had limited use other than successful jack-hammer and dead-blow detection in the immediate vicinity of the monitored CI pipe-section.*

• Wireless Communications

- *Wireless communications was limited to $^1/_4$ mile due to excessive joint-attenuation.*
- *Limited networking was due to the presence of drip-rods in the selected demonstration-area in NY.*
- *Frequency-hopping and the associated sub-optimal waveguide frequency and reduced power seemed to impact range as well.*
- *Multi-unit serial (flattened network topology) master-repeater-slave architecture proved itself to work very well thereby validating the architecture and protocols developed for this application.*

• Packaging and Operational Logistics

- *The use vacuum/purged/pressurized inert-gas enclosures proved to be more than adequate for the use of the wands in field-trial settings.*
- *Due to the monolithic design of the wand/enclosure/etc. the unit was a bit ungainly and prone to damage during minimal-blow installation in CI mains.*

• User Interface

- *The user interface design and data-representation proved to be extremely useful and provide novel insight into the very dynamic nature of a gas mains variables (flow, etc.)*

The above conclusions resulted in a set of recommendations by the AI contractor team to both NYGAS and DoE, primarily for consideration of implementation in a future Phase II effort, and can best be summarized (in no particular order of importance) in varied categories, as follows:

• Sensing Systems

- *Flow-rate measurements based on flow-speed are extremely valuable; a more in-depth calibration and independent verification may be needed to validate the combination of measurement and numerical flow-rate calculation.*
- *Mechanical wall vibration measurements should be repeated in a bolted/welded steel network segment to predict whether such a measurement is useful in the field.*
- *Introduction of an acoustic monitoring system for flow-column noise-monitoring may be of value, as may ultra-low frequency soil-vibration monitoring.*
- *Even though seemingly superfluous, the sensors for pressure, temperature and humidity should be retained to generate trend-data and used for follow-on testing to see if water-intrusion and freeze-thaw cycles can be detected.*
- *Additional/Replacement sensors could be added, subject to the need and review of the NYGAS utility members co-funding the Phase II effort.*

• Wireless Communications

- *Wireless communications ned to be improved along the lines of (i) antenna tuning, (ii) frequency-hopping control, (ii) waveguide frequency selection and (iii) output power* *control and amplification.*

* Antenna tuning should be accomplished through the use of specialized RF power-measurement equipment in future versions.
* Frequency-hopping control is to be included in future versions to channel more power and better select the most suitable frequency band for a given node-to-node installation (not a regulatory issue as in-pipe is not subject to FCC regulations).
* Increase in output-power magnitude and level-control is proposed to be accomplished through teaming and funding an OEM developer for the hardware elements.

- *RF communications ranges in steel pipes should be tested ASAP, given that cast iron links were rather limited in range compared to those measured in a very short steel test-loop that NYGAS funded at CMU. It is proposed that NYGAS query its members to seek the availability of such a line (preferably abandoned to allow the use of the current nodes for range-testing).*

• Design for Modularity

- *The wand-unit should be re-designed to allow for a more straightforward re-utilization (through separation) of the sensor (in-pipe) elements from the processing (data-acquisition and filtering) and communication/storage elements. The goal here is to allow for simpler product diversification for applications where the data-collection is to be in wired (pager or cell), wireless (inside or out-of pipe) or even local data-logging mode. The notion is that a limited suite of sensors can then be coupled with a variety of out-of-pipe processing, storage and communications alternatives without having to re-design all elements for a new product model.*
- *Associated power-, data and wireless interfaces separating the inside form the outside of the pipe need to be carefully considered in terms of standards, safety (IS if below 1W) and hardware implementation.*
- *Additional interfaces for a generic wired or wired-to-wireless interface, as well as local memory-card based interface should be considered.*

• Packaging and Operational Logistics

- *A simplified into-pipe wand unit should be developed to reduce the size and complexity/ handling for ease of installation. This unit should allow for both cast-iron and no-blow steel-main installation.*
- *Sensing electronics should be packaged onto an in-pipe PCB with on-board data-collection, RAM and standardized high-speed I/O, with a protected and IS-level power-consumption. PCB mounting onto different metallic screw-in fittings should be possible depending on whether cast-iron or steel pipes will be used.*
- *External electronics (processing, data-collection and/or communications) should be designed and packaged for easy and rugged connectivity to the pipe-installed sensor-wand; this need not necessarily be done with no-blow tooling (NYGAS utilities to comment). These electronics may also need to be packaged differently if they are not IS-compliant.*
- *Power-source options will need to be considered to suit the application at hand. Short-term (days to weeks) logging should be accomplishable with low-cost local battery technology. Mid-term duration (weeks to months) logging may be possible with local batteries, but wired implementations should be optional.*
- *Buried-access design considerations will need to be considered for the long-term (months to years) data-collection system design, whether it be line- or self-powered, and whether it be used as a data-logger or wire(d)(less) transmitter.*

• User Interface

- *The user interface should be continued and considered as a simple command-interface for re-programming or reconfiguring the network over the existing network link (wired or wireless).*

- *A better interface for viewing historical data (database management and graphics application issues) or ongoing plotted trend-data (XY-plot) should also be considered in a future implementation (not necessarily Phase II)*
- *In a future activity, integrating the existing plate layouts with the known GPS-based location of the nodes would be a feature that would allow for the integration into any utility GIS; again not suggested as a Phase II effort.*

III. APPENDICES

1.0 Acknowledgements

AI wishes to acknowledge the support of DoE-NETL's SCNG through co-funding this work under contract #DEFC26-02NT41320. In addition, we also wish to thank NYGAS for co-funding this effort to date under a separate fund-matching (cash and in-kind) contract.

Special thanks go to Keyspan Energy, Inc., and in particular Mr. Daniel Deletto and Mr. Anthony Savino for facilitating, managing and supervising the week-long field-trial of the ***GasNet***^{TM} system in West Valley, NY in late November 2002.